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Experimental Study of the Effects of Thermal Transients on the Performance Characteristics of Piezoelectric Accelerometers - A Progress Report

Paul S. Lederer

Electronic Technology Division
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

July 15, 1973

Progress Report covering period 9–15–72 to 4–15–73

Prepared for
Lawrence Livermore Laboratory
University of California 94550

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EXPERIMENTAL STUDY OF THE EFFECTS OF THERMAL TRANSIENTS ON THE PERFORMANCE CHARACTERISTICS OF PIEZOELECTRIC ACCELEROMETERS – A PROGRESS REPORT

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This is a progress report. The work is incomplete and is continuing. Results and conclusions are not necessarily those that will be included in the final report.

Prepared for
Lawrence Livermore Laboratory
University of California 94550

U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

Experimental Study of the Effects of
Thermal Transients on the Performance Characteristics
of Piezoelectric Accelerometers

Progress Report for the Period From September 15, 1972 to April 15, 1973.

to the

University of California, Livermore Laboratory
Interagency Agreement #AT(04-3)-911
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Prepared by

P. S. Lederer
Project Leader

1. Introduction

The basic experimental technique used in this investigation involves subjecting two accelerometers to the same vibrational accelerations and exposing one of them simultaneously to a thermal transient. The second accelerometer, which is shielded from the thermal stimulus, is used as control and to monitor the acceleration amplitude to which both instruments are subjected.

2. Description of experimental set-up

The experimental set-up is shown in Figures 1 and 2. The electromagnetic vibration exciter rests on a large brass support plate on a work bench. A covered, aluminum, cup-like structure is fastened to the shaker table. The reference accelerometer is mounted on the bottom of the cup, with its cable passing through a hole in the side wall of the cup. The test accelerometer is mounted on the removable cover plate of the cup. The surfaces on which the accelerometers are mounted are parallel with each other within 1 degree and perpendicular to the direction of vibration within the same tolerance. The vibration exciter is set up so that the direction of vibration is vertical. A metal framework surrounding the vibration exciter carries shielding material, a source of radiant heat energy and a radiation sensor.

The shielding material consists of a square plate of a nonmetallic insulating material about 8 x 8 inches (20.3 x 20.3 cm) supported by the framework about 2 inches (5.1 cm) above the cover plate on which the test accelerometer is mounted. A circular hole in the insulating plate 3 inches (7.6 cm) in diameter is concentric with the test accelerometer position. A sliding shutter of the same insulating material

covers the hole normally, and is pulled away to permit the radiation to pass through the hole in performing the test.

The source of the radiant heat energy is a commercial 600 W quartz-bromine incandescent lamp with an aluminum reflector. Its energy output is adjusted by means of a variable autotransformer fed from the laboratory ac line. The lamp is attached to an arm on the framework which permits it to be positioned directly above the hole in the shield to irradiate the instrument under test. The arm permits the lamp to be swung laterally in the same horizontal plane to position it directly above the absorption head of the radiation monitor.

The radiation monitor is a broadband power meter with a flat response over wavelengths from 0.3 to 30 μm, and full scale power readings of 1, 3, 10, 30, and 100 watts. The meter consists of an absorption head and a control and read-out unit. The absorption head, which is mounted on the tester framework, contains a coated metal disc located at the end of the entrance cone. This disc absorbs the incident radiation over the above range of wavelengths. The periphery of the disc is in intimate thermal contact with the finned, convection cooled, heat sink of the absorption head, and the resultant radial heat flow is sensed by a concentric system of thermocouples (thermopile) mounted to the back surface of the disc. The voltage generated by the thermopile is amplified in the control unit and is displayed on the meter which is part of the unit.

The distance of the sensing disk from the radiation source is identical to the distance of the accelerometer from the source when measurements are made.

The remainder of the test set-up consists of signal conditioning and display devices for the accelerometer output signals and a power amplifier and function generator to drive the electromagnetic vibration exciter.

The signal conditioning equipment consists of a commercial charge amplifier for the reference accelerometer and another charge amplifier of the same type or, alternately, an electrometer amplifier, for the test accelerometer. The outputs can be displayed or recorded on an oscilloscope or oscillograph. Prior to the start of the experiments, a patch panel had been constructed which was designed to facilitate the work. The cables from the two accelerometers plug into connectors on the panel, as do cables leading to-and-from the amplifiers. Additional outlets lead to a monitoring oscilloscope and to two channels of the recorder. Finally, there is a provision for feeding the output of either channel to a precision ac rms meter.

During the initial experiments which were designed primarily to explore the general operation of the test set-up, one of the charge amplifiers showed excessive instability and was returned to the manufacturer for repair. Also, a malfunctioning potentiometer in the shaker drive amplifier was replaced.

When the repaired charge amplifier was returned, both charge amplifiers were calibrated over the range of possible settings and operating conditions used with the accelerometers to be tested. Those accelerometers (including the one used as the reference accelerometer) fall into four ranges of sensitivity, roughly 0.03 pC/g, 0.15 pC/g, 15 pC/g, and 60 pC/g. Since most of the tests were expected to be run at a level of 10 g (0 to peak), the charge amplifiers were calibrated with those settings of sensitivity and range which would produce a nominal 1 volt (0 to peak) output at this acceleration level. Most tests were planned to be performed at 100 Hz, consequently this frequency was selected as the reference frequency.

The choice of this frequency was based on two considerations: it is a frequency above the anticipated low roll-off frequency caused by amplifier-accelerometer time constants, and well below any frequencies at which a difference in phase or amplitude of the test and reference accelerometers might occur. Also, it was desirable for recording purposes that the frequency be within the response capabilities of the galvanometers of the oscillograph available. A frequency of 100 Hz met these criteria.

3. Charge amplifier calibrations

The reduced data from the charge amplifier calibrations are shown in Tables I through VI. Voltage output in all cases was a nominal 1 volt (0 to peak), except for the 0.03 pC/g accelerometer setting which produced only 0.1 volt (0 to peak). The calibrations were performed by feeding known voltages through known capacitances (either the built-in 100 pF ±0.5% calibration capacitor or an external 1000 pF ±0.05% precision capacitor, depending on the range used) into the charge amplifier and measuring the resultant output voltages. This was done at several frequencies and for the three time constant settings available on the charge amplifier. The data were reduced in each case by calculating the output voltage which should have resulted from the known input, sensitivity setting and range setting, and dividing this value into the actual output. From these values, frequency response ratios were calculated with reference to the 100 Hz, short time constant, voltage ratio as reference on each range.

The ratios of the actual output to the calculated output at 100 Hz for all test conditions of the reference charge amplifier (A) ranged from 0.961 to 1.015 (a spread of ±2.8%), for the test charge amplifier (B) from 0.976 to 1.055 (a spread of ±4.0%).

4. Exploratory thermal transient tests with charge amplifier

Following the calibrations of the charge amplifiers, a series of experiments was performed to explore the effects of test condition variations, in order to arrive at an optimum set of test conditions for producing useful data.

For these tests an old, but satisfactorily operating, compression accelerometer with a charge sensitivity of 14.3 pC/g was used in conjunction with the test charge amplifier. Another piezoelectric accelerometer was used as the shielded reference. Tests were performed to explore the effects of test frequency, test acceleration level, lamp power, lamp distance, charge amplifier time constant, and exposure time. The test conditions for all (except for parameter variations specified) were the following: lamp distance 7.5 inches (19.1 cm), lamp power 1 watt, test frequency 100 Hz, acceleration level 5 g (0 to peak), exposure time 15 seconds, amplifier range setting 100 g/volt, time constant: short.

Figure 3 shows the effects of the radiant energy level on the zero shift of the accelerometer-charge amplifier system. In this test, power levels of 0.5, 1.0, 1.5, 2.0, and 2.5 watts were used. It can be seen that after an initial delay of about five seconds following shutter opening after an initial small negative going shift, the zero output showed a relatively linear increase with time. The zero shift continued for five seconds after the shutter was closed, and then began to reverse direction. The amount of zero shift at any time from about 5 to 20 seconds after exposure began was found to be roughly proportional to the radiant power level, reaching about 20 g after 15 seconds at 1.0 watt.

Tests run at frequencies of 20, 50, 100, 500, and 1000 Hz, (shown in Figure 4) and those at acceleration levels of 2, 4, 6, and 8g(0 to peak), as anticipated, show that neither frequency nor acceleration levels had any significant effect on results.

Tests performed with different time constant settings of the charge amplifier show substantial differences as demonstrated by the graphs in Figure 5. The short time constant test shows the same general characteristics as observed previously (see Figure 3), although its maximum zero shift was less than that in the previous test. This is believed due to scaling difficulties since the recorder's deflection sensitivity was set quite low, to permit complete display of the recordings at the other time constants. The maximum zero shift observed was about 18 g at about 21 seconds with the short time constant (10 seconds). With the medium time constant (1000 seconds), the maximum zero shift, reached after 40 seconds, was about 210 g. With the long time constant (10^6 seconds), the maximum shift was about 285 g after 50 seconds.

Medium and long time constant settings are very difficult to use in tests with most piezoelectric accelerometers due to the large, random drifts in charge amplifier output caused by minute accelerometer temperature changes, cable flexing, small environmental vibrations etc. Furthermore, these time constants are rarely used in measurement, the long time constant is recommended only for quasi-static calibrations of transducers with low internal leakage, such as quartz crystal pressure transducers.

In view of these limitations we feel that a useful experimental technique should generally employ the short time constant setting on the charge amplifier unless, due to constraints imposed by a required range setting, the resultant time constant is less than the time duration of the test stimulus. Nevertheless, it is important to realize that thermal transient test data obtained at short time constant settings can be highly misleading if the longer time constant settings are used for any actual measurements with the same piezoelectric accelerometers.

The results from tests performed with different durations of thermal energy exposure are shown in Figure 6. The data appear to indicate that the thermal gradients set up within the accelerometer stabilize after about 38 seconds, causing the observed zero shift to show no further increase after that time. Actually, this is probably not entirely true since the charge amplifier time constant (10 seconds) is such that the rate of voltage decay in the feedback circuit matches the rate of charge build-up in the accelerometer. Thus, tests with different time constants or at other range settings of the charge amplifiers are expected to produce different results. This requires further investigation.

A test performed with the radiation source at various distances from the test accelerometer, ranging from 3 inches (7.5 cm) to 10 inches (25.4 cm), produced data which indicated that greater zero shifts occurred when the lamp was farther away. This was contrary to expectations. It may be caused by the difference in spectral content at the different source temperatures required to produce 1 W incident on the accelerometer, and spectral differences in absorbtivity of the metal shell of the accelerometer might come into play. This will also be investigated further.

Finally, during the test at which the accelerometer was exposed to different power levels (see Figure 3), attempts were made to measure any changes in sensitivity in addition to zero shift. Due to the small changes involved, the results were not wholly consistent. It does appear, however, that a maximum sensitivity shift of 3% occurred after about 15 seconds at 2.5 watts and somewhat smaller changes at the lower power levels.

5. Exploratory thermal transient tests with electrometer amplifier

One of the basic characteristics of the design of the charge amplifier is the change in time constant with range, since the range changing component is a capacitor in the feedback loop. This feature would make it more difficult to make valid comparison during these tests between accelerometers of widely differing sensitivities.

Accordingly a series of experiments was performed using a commercial electrometer amplifier. This instrument has a number of voltage ranges, as well as a control for changing its input resistance independently of the voltage range setting. The actual input resistance values available are 10^{14} ohms, and from 10^{11} ohms downward in decade ranges.

Two accelerometers supplied by the Lawrence Radiation Laboratory were used in these tests. Accelerometer (A) a "general purpose charge accelerometer"(compression type) with top connector and electrical isolation has a nominal charge sensitivity of 13 pC/g, a capacitance of 2700 pF and a range of ±1000 g. Accelerometer (B), a "shock accelerometer" (shear type), with top connector, has a nominal charge sensitivity of 0.03 pC/g, a capacitance of 115 pF and a range of -20,000 g, + 100,000 g. The nominal voltage sensitivities of the two instruments with 300 pF external capacitance (representing about 10 ft (3 m) of the standard connecting cable) is 4 mV/g for accelerometer (A), and 0.06 mV/g for accelerometer (B).

The test conditions for these tests (except for the parameter variation specified) were the following: lamp distance 7.5 inches (19.1 cm), lamp power 5 watts, test frequency 100 Hz, acceleration level 15 g (0 to peak), exposure time 15 seconds, input resistance 10^9 ohms.

In all of these tests, the electrometer output was displayed on an oscilloscope and photographic records taken of the resulting traces. The output of the monitoring accelerometer system was measured with the aid of the ac voltmeter. Data from the photographs were reduced with knowledge of the displayed acceleration level and the 'scope preamplifier attenuator settings.

The effect of input resistance on zero shift was investigated first. Results, shown in Figures 7 and 8, indicate, as expected, that the apparent zero shift is greater for large values of input resistance. As before, a time constant short compared to the duration of the thermal transient tended to mask the effects of the transient. The effect of radiation power level on zero shift is shown in Figure 9 for both accelerometers. As with the charge amplifier tests described earlier, the effect increased with increased power level. And again, as in the earlier tests, there is no significant effect on the

magnitude or shape of the zero output characteristics caused by testing at acceleration levels of 5 g or 15 g (0 to peak). This can be seen in Figure 10A, which shows test data for accelerometer (A). Figure 10B confirms that different voltage range settings of the electrometer amplifier also have no effect on the apparent zero shift observed.

6. Further tests with charge amplifier

The two test accelerometers were tested again, but with the charge amplifier instead of the electrometer as in section (5). The results obtained are shown in Figures 11 and 12. Tests were performed at 100 Hz, 5 g (0 to peak), and power levels of 5 watts and 10 watts at a variety of range settings. The shapes of the curves obtained from these tests are quite similar to those obtained with the electrometer, and are shown in Figure 9.

Considering accelerometer (A) at a charge amplifier range setting of 200 (described by the amplifier manufacturer as resulting in a time constant of 2 seconds), the zero shift after 15 seconds at 5 watts was found to be -60 g (Figure 12). Using the electrometer with an input resistance of 10^9 ohms, which teamed with a combined accelerometer and cable capacitance of 3000 pF results in a time constant of 3 seconds, the zero shift observed after 15 seconds at 5 watts was -110 g (Figures 7 and 9).

In the case of accelerometer (B), at a charge amplifier setting of 10 (time constant 0.1 second), zero shift after 15 seconds at 5 watts was +80 g (Figure 11). Using the electrometer, the time constant (10^9 ohms x 400 pF) was 0.4 seconds, and the observed zero shift after 5 seconds at 5 watts was +80 g.

7. Preliminary conclusions

From the work done so far it appears that comparisons of the effects of thermal transients on piezoelectric accelerometers should probably be done with the aid of the electrometer so as to be unhampered by gain-time constant constraints. To get an idea of the actual accelerometer measurement performance, which will most likely involve the use of a charge amplifier, the latter should be used in testing. Accordingly we feel it desirable that all accelerometers be tested using both methods. The test data also indicate that operation at 100 Hz and 5 g (0 to peak) appears optimum from the point of view of shaker capability, output signal magnitude, and ability to calibrate the system.

The time constants used in both methods are of the order of, or shorter, than the 15 second radiant heat exposure used in these tests. Longer time constant settings on the charge amplifier (or high values of electrometer input resistance) tend to result in considerable amounts of output signal instability, large enough to mask the effects of the thermal transients.

8. Future Efforts

We plan to investigate in more detail operation with longer time constants. We will also, however, attempt to shorten the exposure time of the accelerometer, to enable adequate testing using the shorter time constants. This will probably necessitate construction of a mechanical shutter arrangement to control the radiation energy beam. Operation with short exposure times will probably also require a higher beam power level, so as to produce a reasonably large output signal. As indicated earlier, we plan to conduct these tests on all accelerometers with the charge amplifier as well as the electrometer. The question of possible spectral effects will also be resolved.

TABLE I

CALIBRATION OF REFERENCE CHARGE AMPLIFIER (A)
AT INPUT EQUIVALENT TO 10g 0 TO PEAK

Accelerometer Sensitivity pC/g	Charge Amplifier Settings			Frequency Hz	Output Ratio Measured/Calculated	*Frequency Response %
	Range g/V	Sensitivity pC	Time Constant			
0.03	1	3.0	Short	10	0.588	60.4
				50	0.946	97.1
				100	0.974	100.0 *
				500	0.986	101.2
				1000	0.989	101.5
				10kHz	1.002	102.9
0.03	1	3.0	Medium	10	0.933	95.8
				50	0.947	97.2
				100	0.961	98.7
				500	0.985	101.1
				1000	0.988	101.4
				10kHz	1.000	102.7
0.03	1	3.0	Long	10	1.006	103.3
				50	1.011	103.8
				100	1.015	104.2
				500	1.022	104.9
				1000	1.024	105.1
				10kHz	1.033	106.1
60	100	6.0	Short	10	0.987	100.0
				50	0.987	100.0
				100	0.987	100.0 *
				500	0.988	100.1
				1000	0.988	100.1
				10kHz	0.988	100.1
60	100	6.0	Medium	10	0.987	100.0
				50	0.987	100.0
				100	0.987	100.0
				500	0.987	100.0
				1000	0.987	100.0
				10kHz	0.988	100.1
60	100	6.0	Long	10	0.987	100.0
				50	0.988	100.1
				100	0.988	100.1
				500	0.988	100.1
				1000	0.988	100.1
				10kHz	0.988	100.1

*Note: Frequency Response Referred to 100 Hz - Short Time Constant

TABLE II

CALIBRATION OF REFERENCE CHARGE AMPLIFIER (A)
AT INPUT EQUIVALENT TO 10g 0 TO PEAK

Accelerometer Sensitivity pC/g	Charge Amplifier Settings			Frequency Hz	Output Ratio Measured/Calculated	*Frequency Response %
	Range g/V	Sensitivity pC	Time Constant			
0.15	1	1.5	Short	10	57.8	59.4
				50	94.6	97.2
				100	97.3	100.0 *
				500	98.6	101.3
				1000	98.8	101.5
				10000	99.4	102.2
15	100	1.5	Short	10	100.0	100.1
				50	99.9	100.0
				100	99.9	100.0 *
				500	99.9	100.0
				1000	99.8	99.9
				10000	97.8	97.9

*Note: Frequency Response Referred to 100 Hz - Short Time Constant

TABLE III

CALIBRATION OF REFERENCE CHARGE AMPLIFIER (A)
AT VARIOUS ACCELERATION LEVELS

Accelerometer Sensitivity pC/g	Charge Amplifier Settings			Frequency Hz	Output Ratio Measured/Calculated	Equivalent Acceleration Level g
	Range g/V	Sensitivity pC	Time Constant			
0.03	1	1.5	Short	100	97.4 97.4 97.6	5 10 20
0.15	1	1.5	Short	100	97.3 97.3 97.6	5 10 20
15	100	1.5	Short	100	98.7 99.9 99.0	5 10 20
60	100	6.0	Short	100	98.8 98.7 98.7	5 10 20

TABLE IV

CALIBRATION OF TEST CHARGE AMPLIFIER (B)
AT INPUT EQUIVALENT TO 10g 0 TO PEAK

Acceleration Sensitivity pC/g	Charge Amplifier Settings			Frequency Hz	Output Ratio Measured/Calculated	*Frequency Response %
	Range g/V	Sensitivity pC	Time Constant			
0.03	1	3.0	Short	10	0.635	62.4
				50	0.988	97.1
				100	1.017	100.0 *
				500	1.034	101.7
				1000	1.042	102.5
				10000	1.068	105.0
0.03	1	3.0	Medium	10	0.964	94.8
				50	0.983	96.7
				100	0.996	97.9
				500	1.027	101.0
				1000	1.038	102.1
				10000	1.066	104.8
0.03	1	3.0	Long	10	1.044	102.7
				50	1.048	103.0
				100	1.055	103.7
				500	1.065	104.7
				1000	1.070	105.2
				10000	1.065	104.7
60	100	6.0	Short	10	0.985	99.9
				50	0.986	100.0
				100	0.986	100.0 *
				500	0.986	100.0
				1000	0.986	100.0
				10000	0.986	100.0
60	100	6.0	Medium	10	0.985	99.9
				50	0.985	99.9
				100	0.985	99.9
				500	0.985	99.9
				1000	0.985	99.0
				10000	0.986	100.0
60	100	6.0	Long	10	0.977	99.1
				50	0.986	100.0
				100	0.977	99.1
				500	0.986	100.0
				1000	0.986	100.0
				10000	0.986	100.0

*Note: Frequency Response Referred to 10 Hz - Short Time Constant

TABLE V

CALIBRATION OF TEST CHARGE AMPLIFIER (B)
AT INPUT EQUIVALENT TO 10g 0 TO PEAK

Accelerometer Sensitivity pC/g	Charge Amplifier Settings			Frequency Hz	Output Ratio Measured / Calculated	*Frequency Response %
	Range g/V	Sensitivity pC	Time Constant			
0.15	1	1.5	Short	10	61.8	61.3
				50	98.0	97.2
				100	100.8	100.0 *
				500	102.5	101.7
				1000	103.3	102.5
				10000	105.3	104.5
15	100	1.5	Short	10	97.6	100.0
				50	97.7	100.1
				100	97.6	100.0 *
				500	97.7	100.1
				1000	97.7	100.1
				10000	97.6	100.0

*Note: Frequency Response Referred to 100 Hz - Short Time Constant

TABLE VI

CALIBRATION OF TEST CHARGE AMPLIFIER AT VARIOUS ACCELERATION LEVELS

Acceleration Sensitivity pC/g	Charge Amplifier Settings			Frequency Hz	Output Ratio Measured/Calculated	Equivalent Acceleration Level g
	Range g/V	Sensitivity pC	Time Constant			
0.03	1	1.5	Short	100	101.8	5
					101.7	10
					102.0	20
0.15	1	1.5	Short	100	100.8	5
					100.8	10
					101.0	20
15	100	1.5	Short	100	98.1	5
					97.6	10
					98.0	20
60	100	6.0	Short	100	98.4	5
					98.6	10
					98.6	20

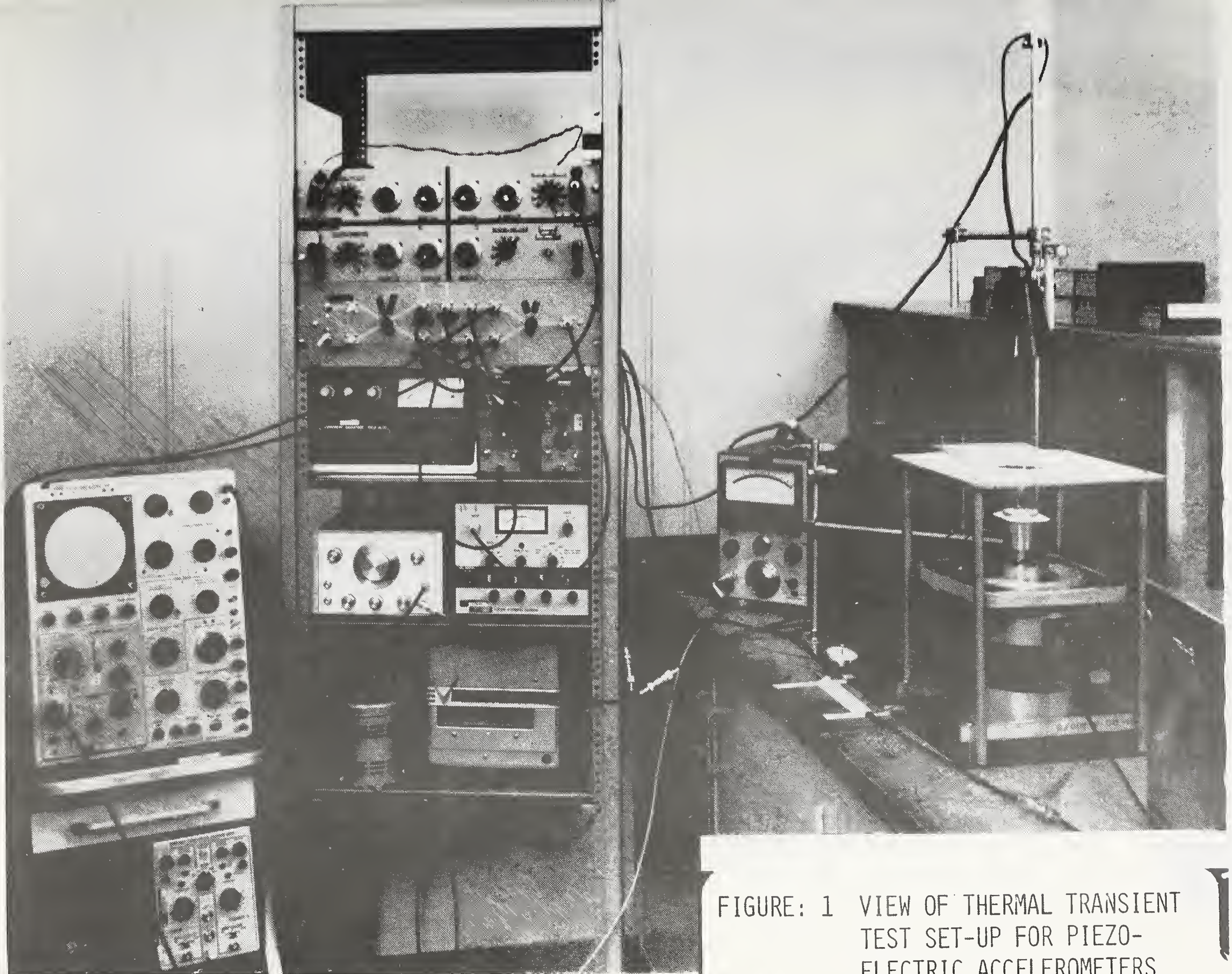

FIGURE: 1 VIEW OF THERMAL TRANSIENT TEST SET-UP FOR PIEZO-ELECTRIC ACCELEROMETERS

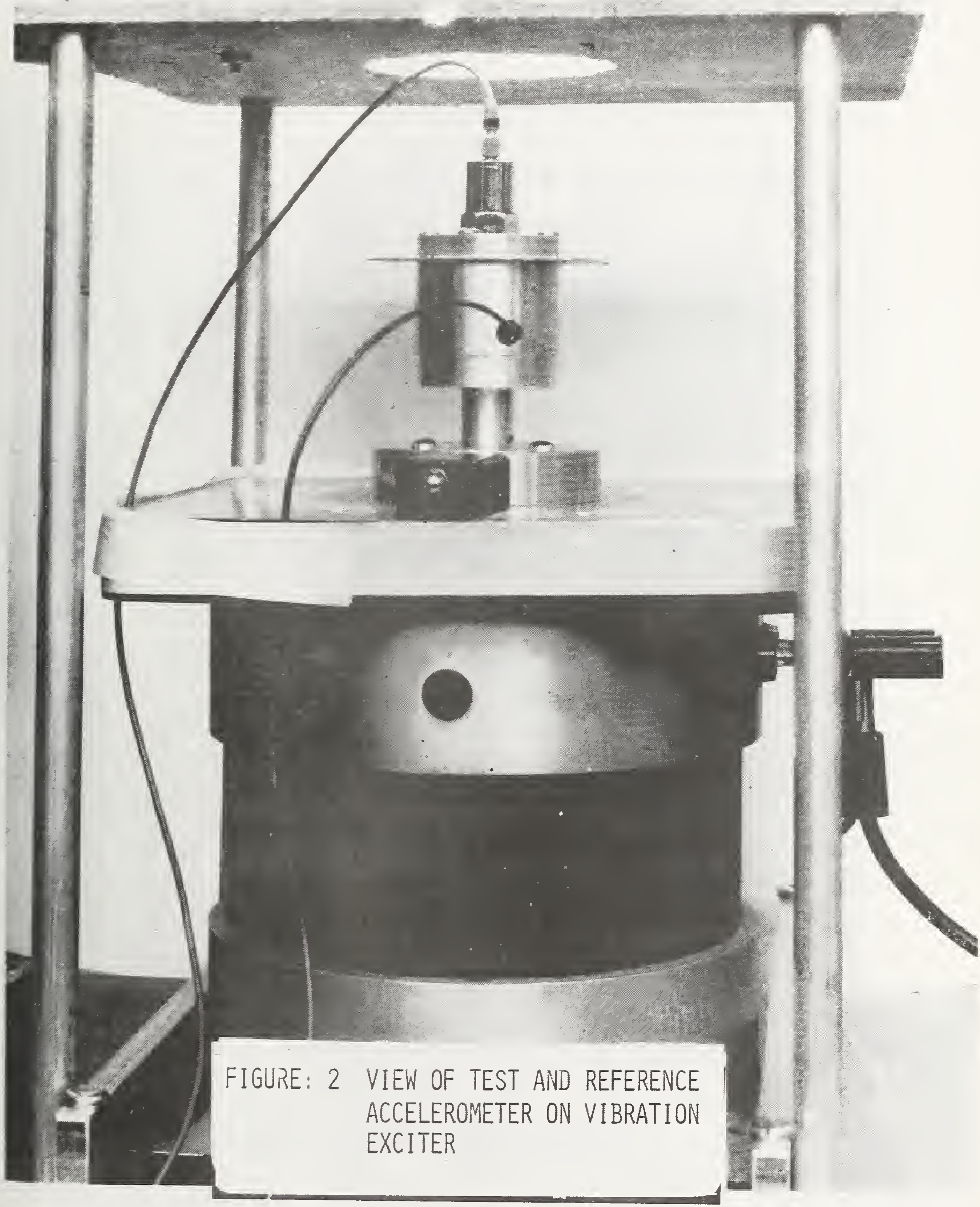

FIGURE: 2 VIEW OF TEST AND REFERENCE ACCELEROMETER ON VIBRATION EXCITER

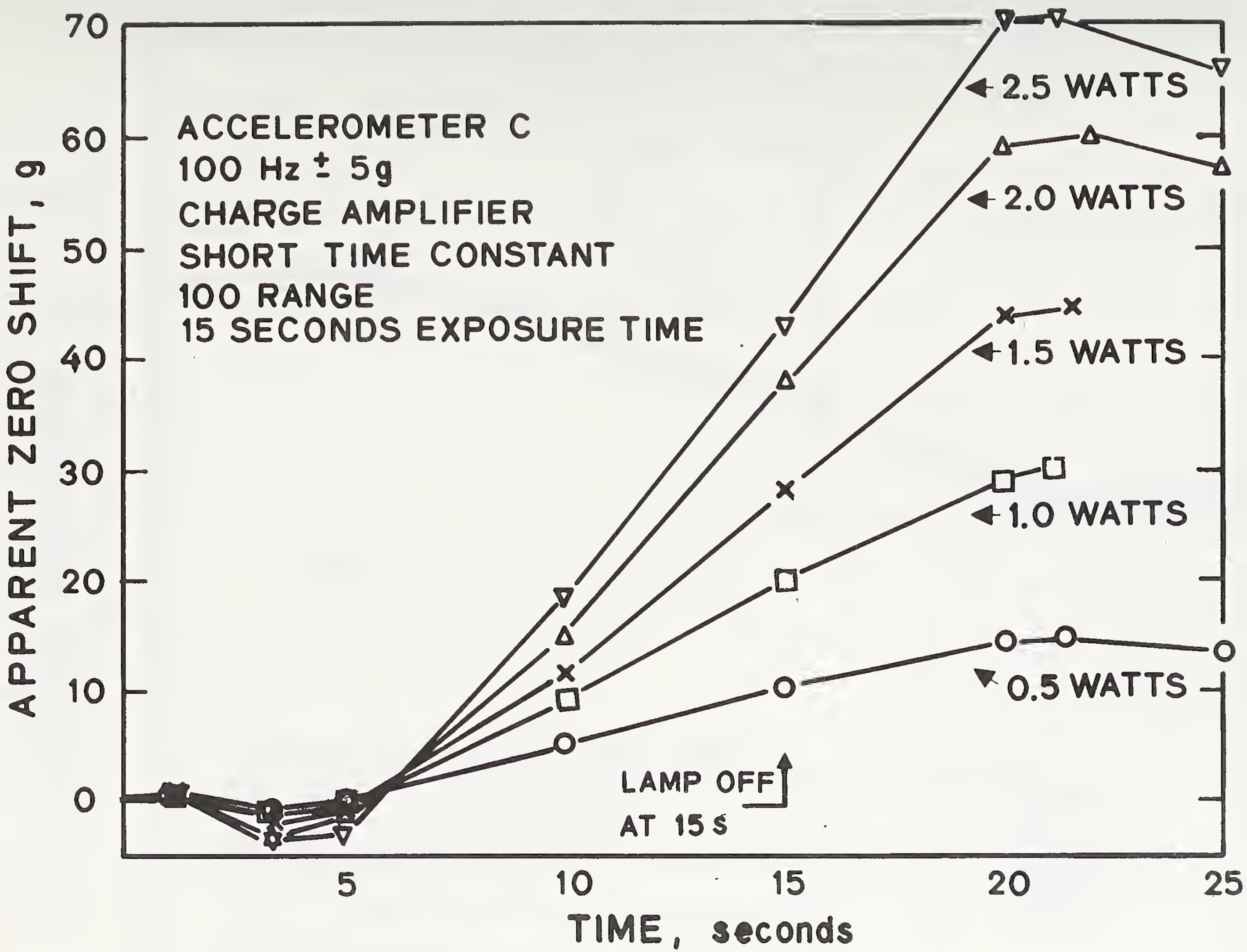

FIGURE 3. APPARENT ZERO SHIFT AS A FUNCTION OF POWER LEVEL.

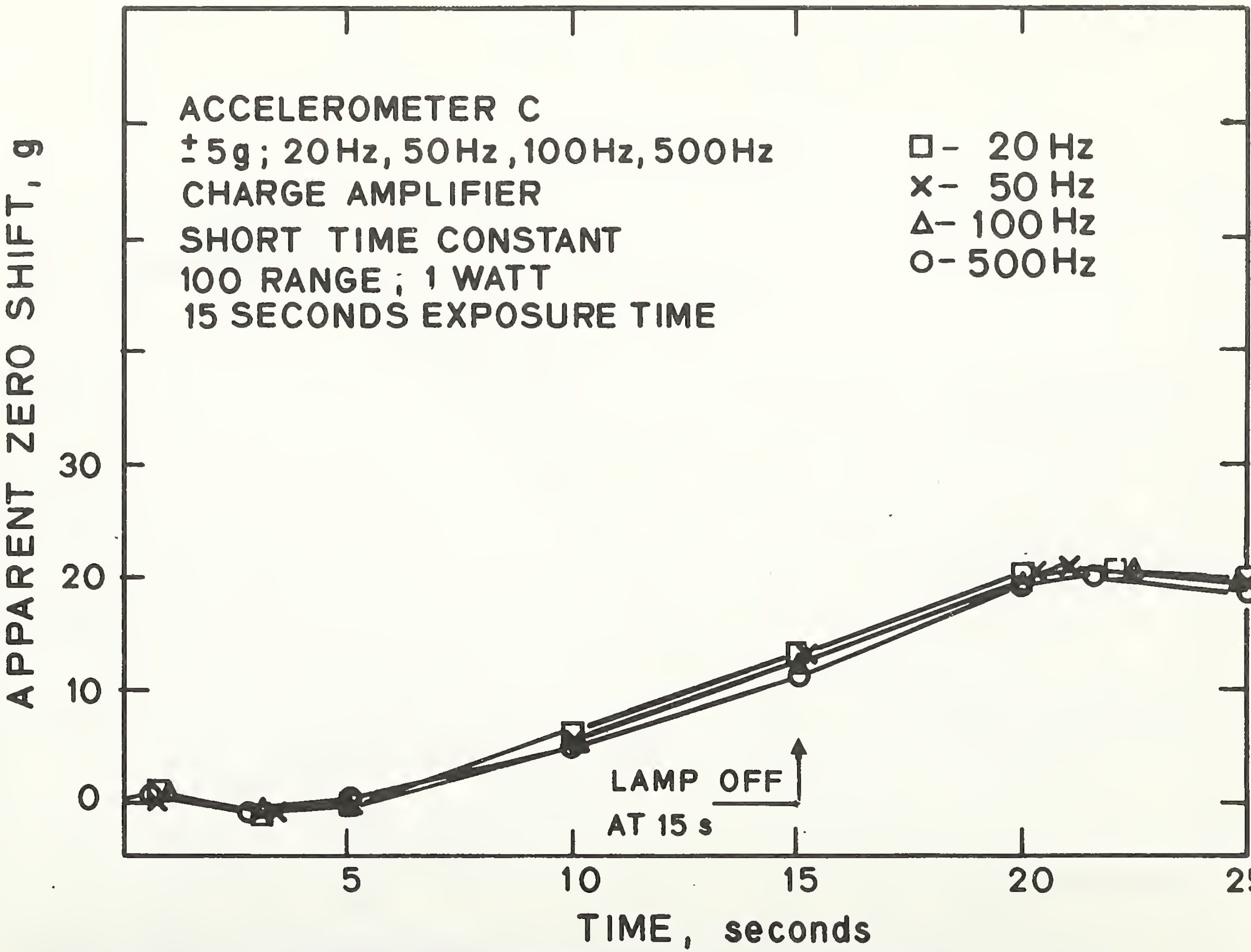

FIGURE 4. APPARENT ZERO SHIFT AS A FUNCTION OF FREQUENCY.

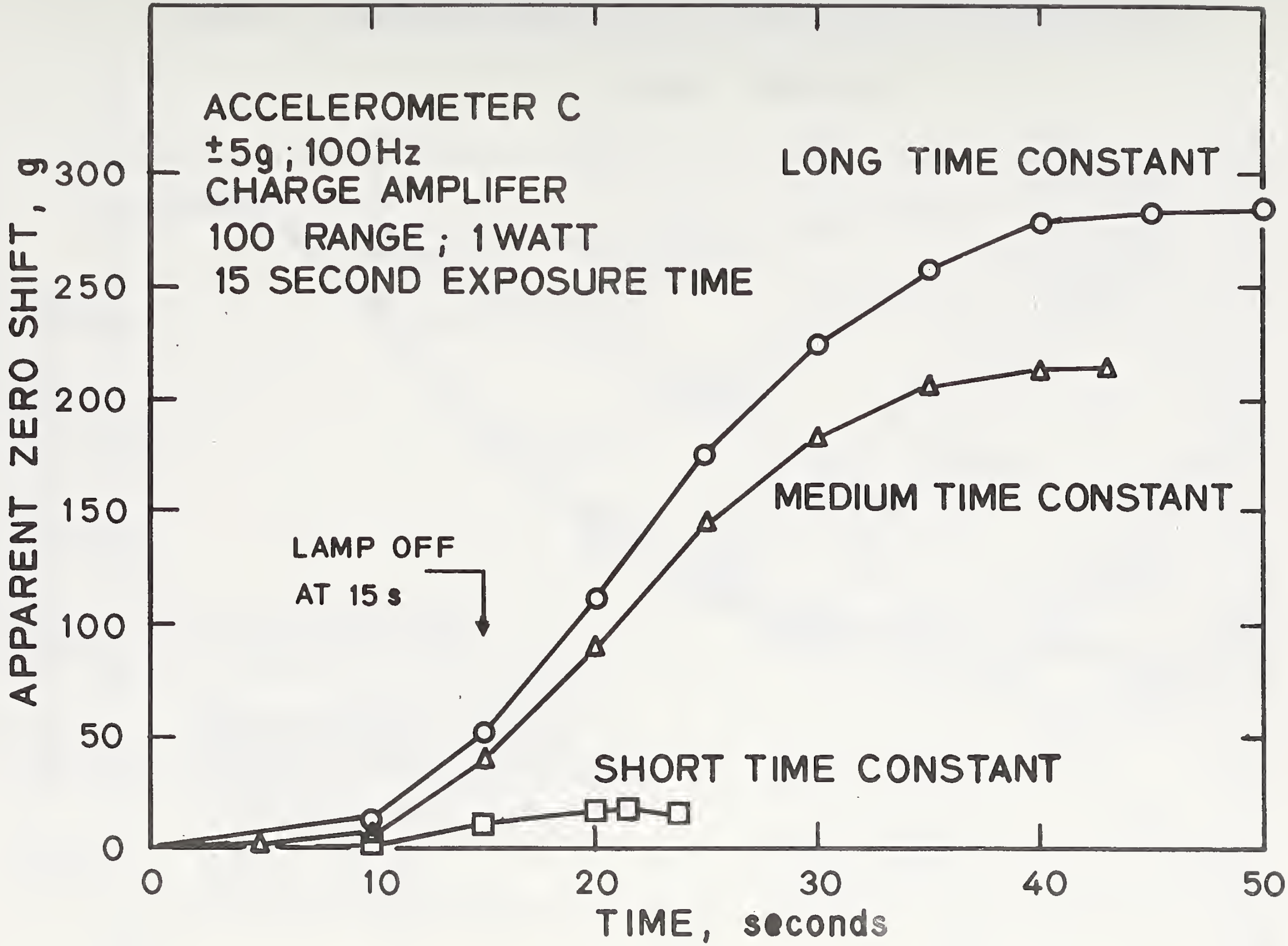

FIGURE 5. APPARENT ZERO SHIFT AS A FUNCTION OF TIME CONSTANT.

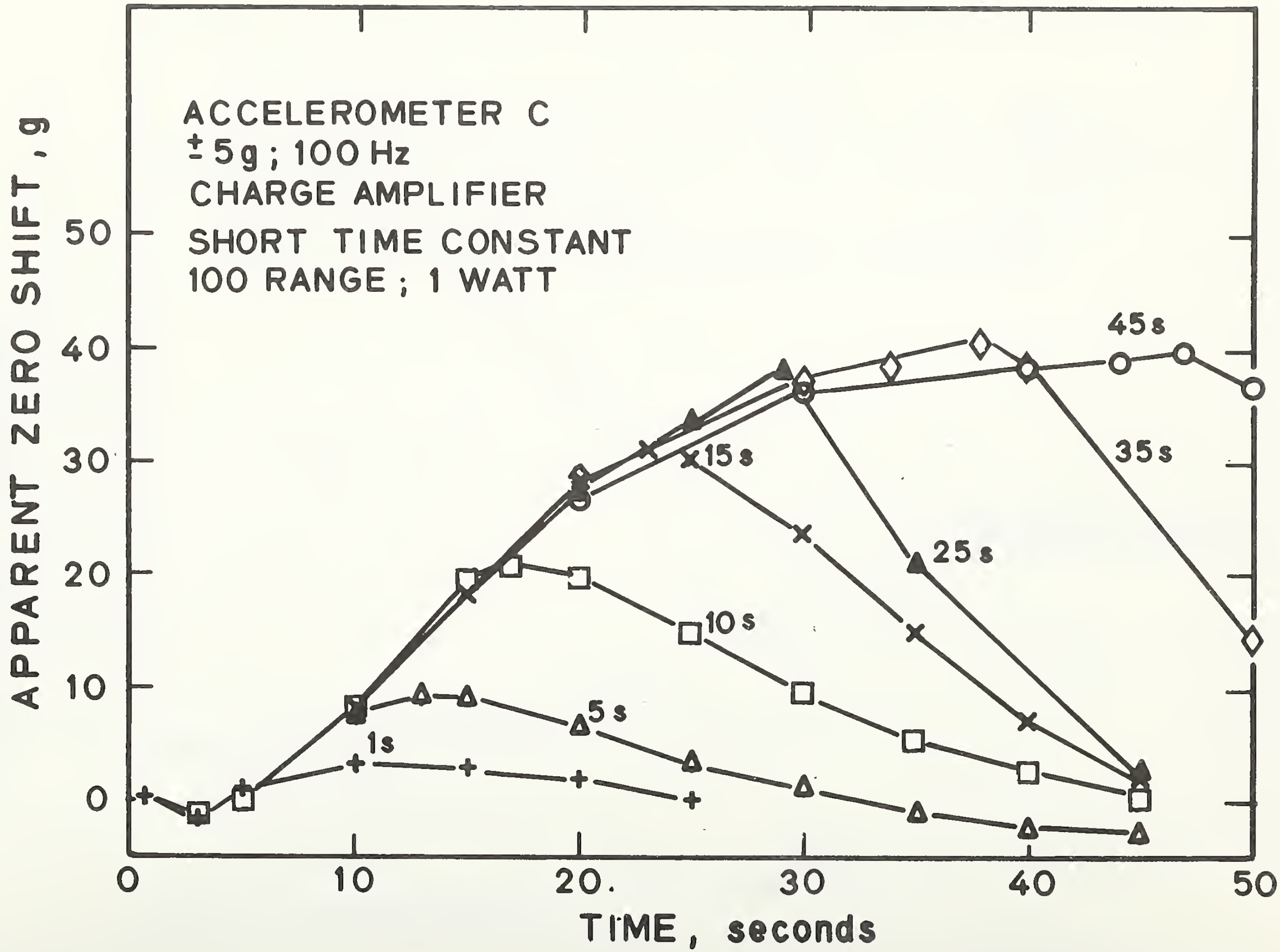

FIGURE 6. APPARENT ZERO SHIFT AS A FUNCTION OF EXPOSURE TIME.

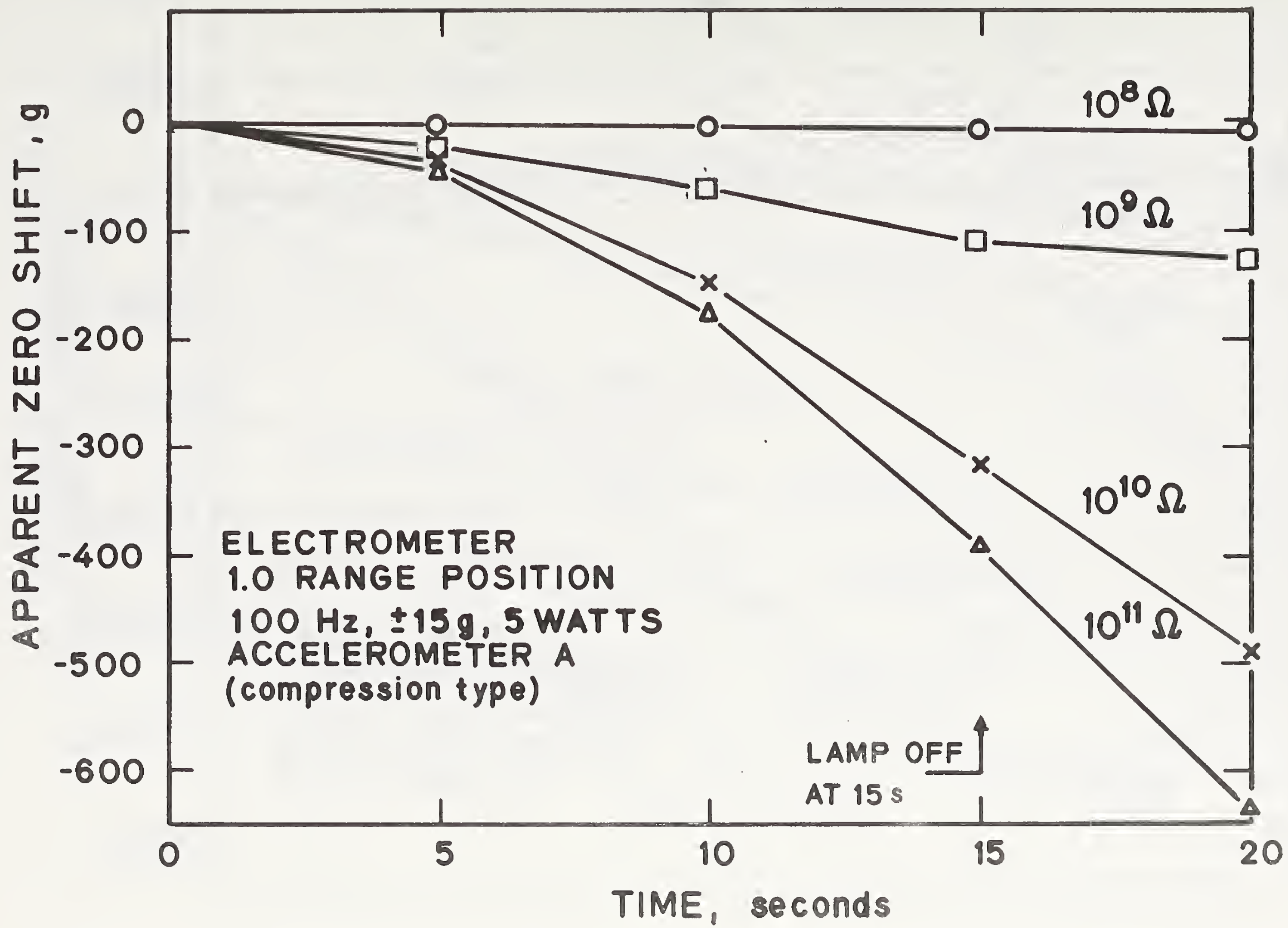

FIGURE 7. APPARENT ZERO SHIFT AS A FUNCTION OF ELECTROMETER INPUT IMPEDANCE.

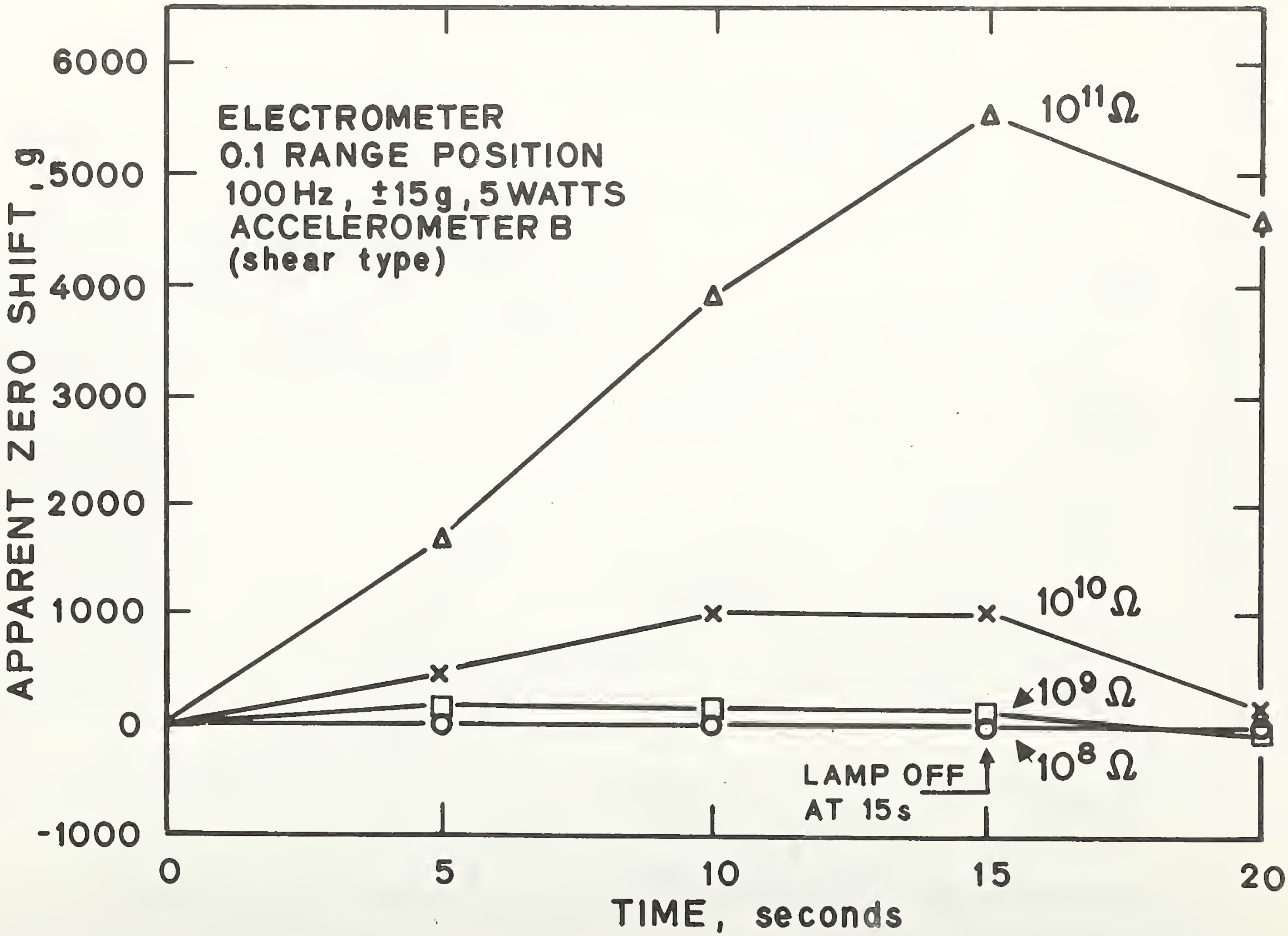

FIGURE 8. APPARENT ZERO SHIFT AS A FUNCTION OF ELECTROMETER INPUT IMPEDANCE.

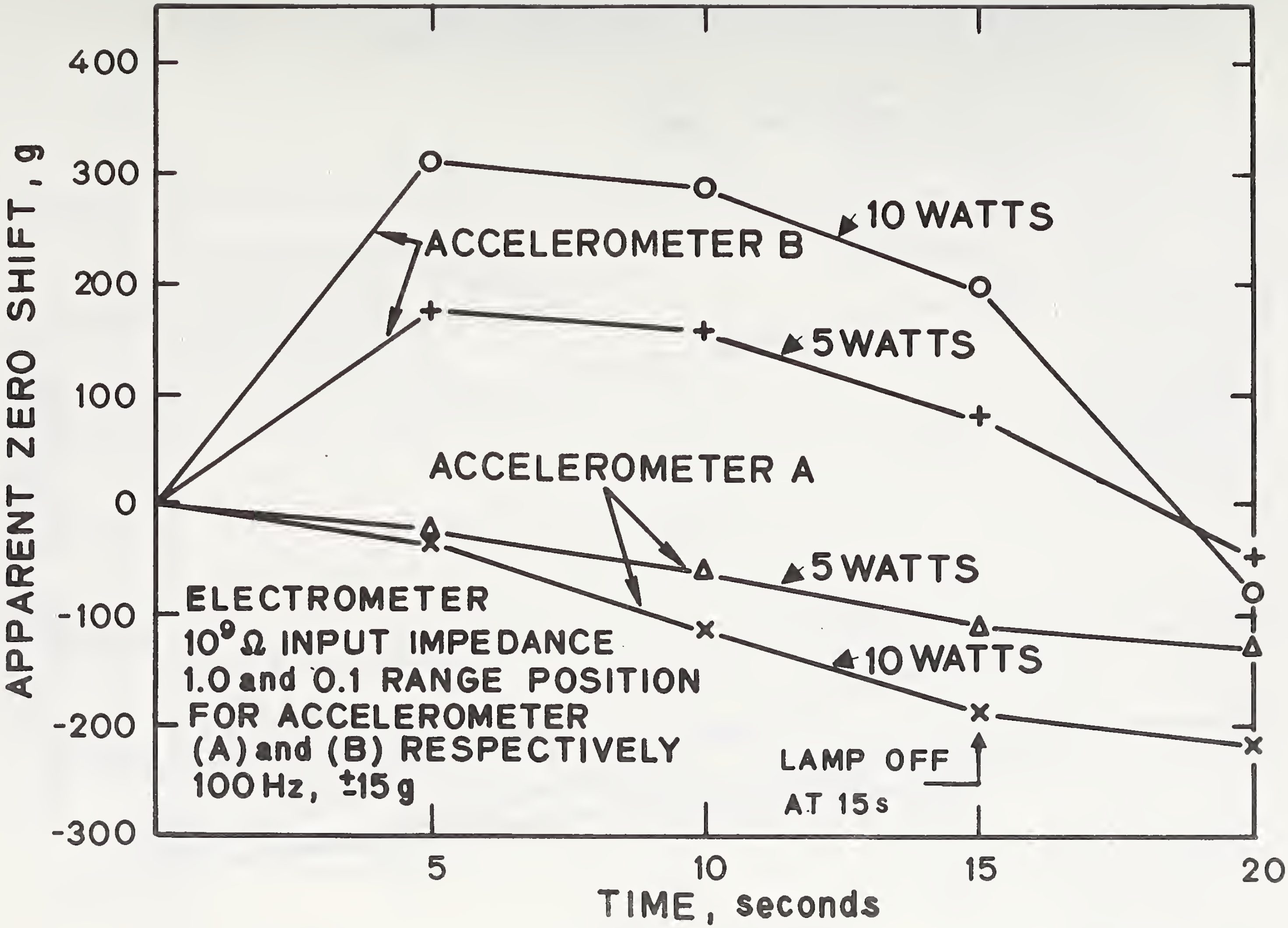

Figure 9. Apparent zero shift as a function of radiation power level.

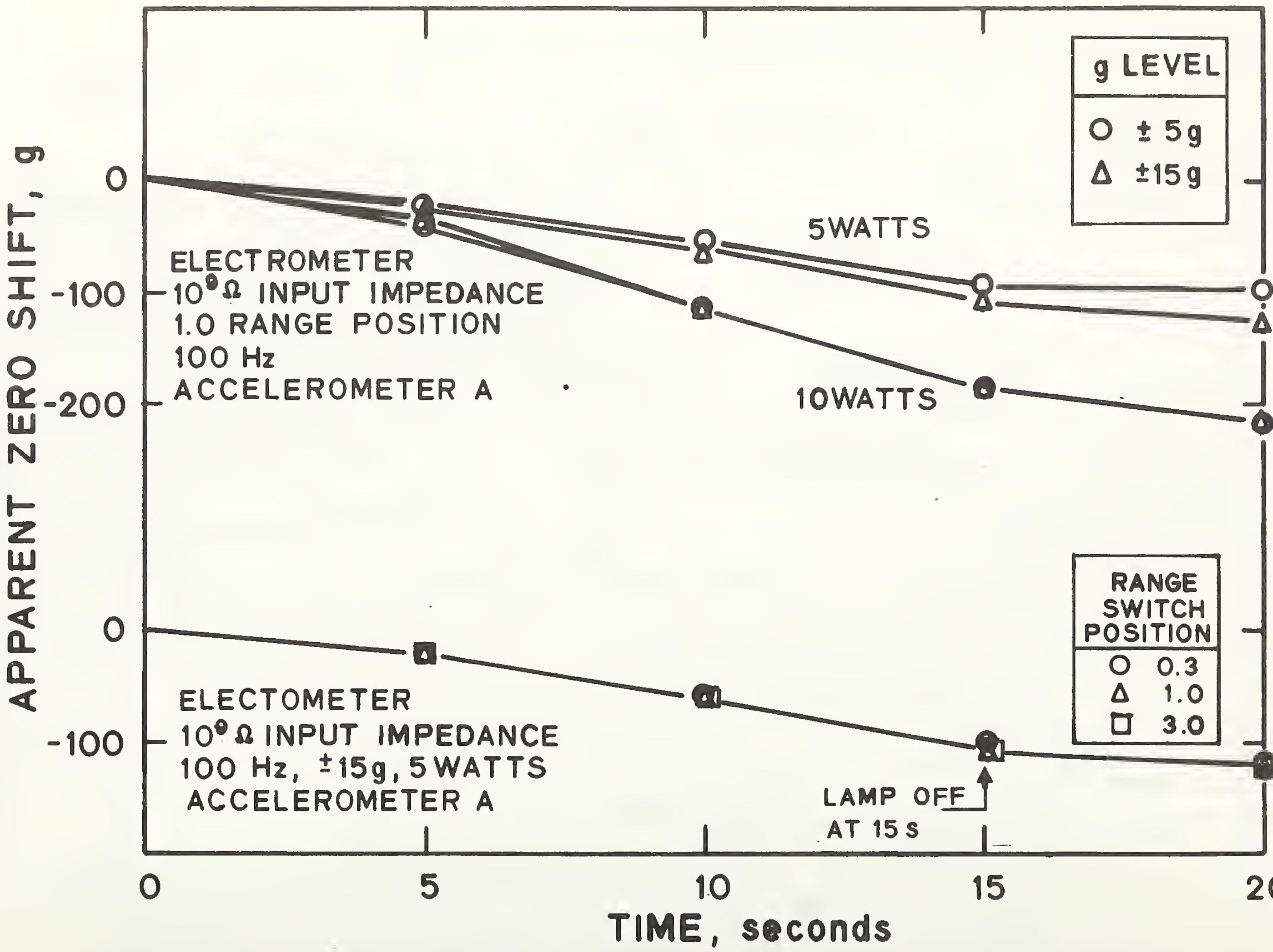

Figure 10. Apparent zero shift with g level and range switch.

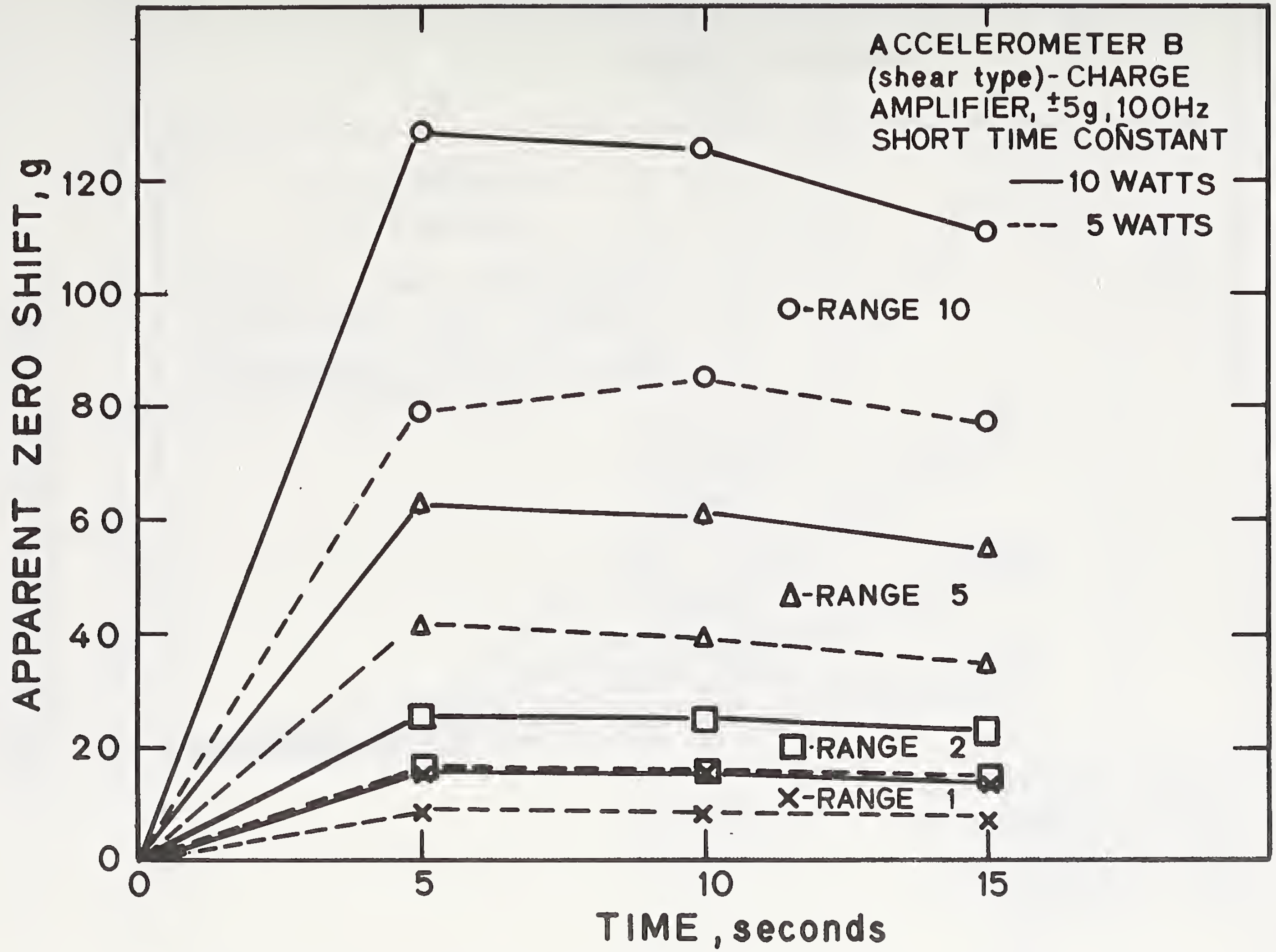

FIGURE 11. APPARENT ZERO SHIFT AS A FUNCTION OF RANGE SWITCH POSITION.

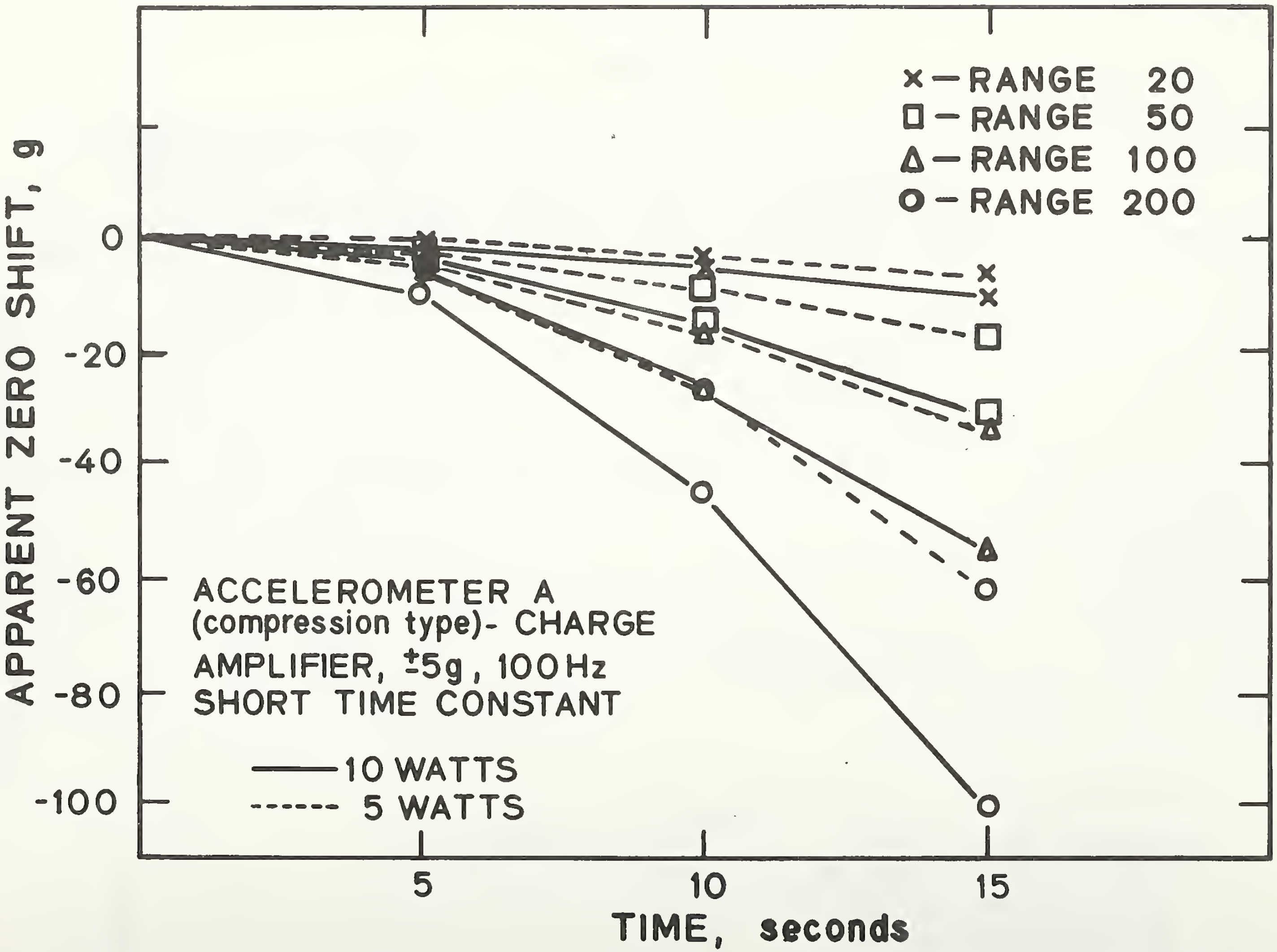

FIGURE 12. APPARENT ZERO SHIFT AS A FUNCTION OF RANGE SWITCH POSITION.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This progress report describes the development of an experimental technique for subjecting piezoelectric accelerometers to controlled thermal transients. It involves the exposure of a vibrating test accelerometer to radiation from a high power incandescent lamp. A second accelerometer, shielded from the radiation, monitors the vibration amplitude. Considerations pertaining to the characteristics of the electronic readout equipment, and their effects on the measurements, are discussed.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Accelerometer; Charge Amplifier; Electrometer; Piezoelectric; Pyroelectric; Thermal Transient

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